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Disclaimer

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Outline

- Applications of time-integrated X-ray imaging at NIF
- Charge-Injection Device (CID) imaging sensor characteristics
- CID Camera X-ray Imager (CCXI) system implementation at NIF
  — Mechanical Design
  — Electrical Design
- CCXI calibration
- CCXI preliminary performance data and radiation hardness at NIF
- Conclusions and Future Work

Collaborators

- National Security Technologies, LLC (NSTec, Livermore Operations)
  — M. J. Haugh, J. J. Lee, E. D. Romano

There Are Many Applications of Time-integrated X-ray Imaging at NIF

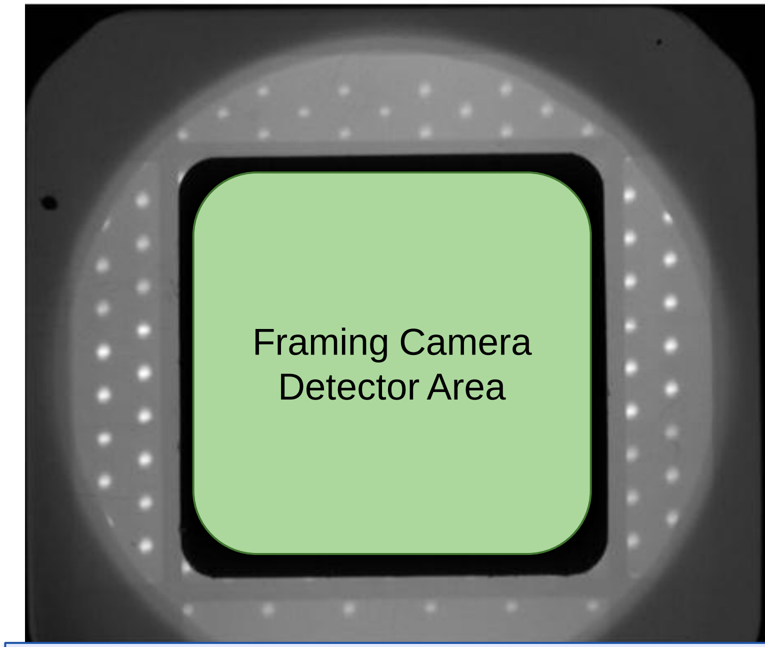
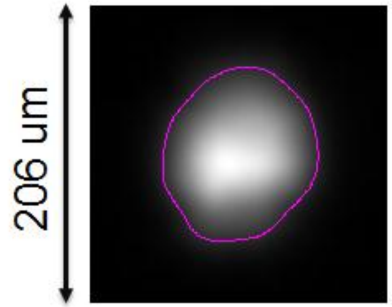
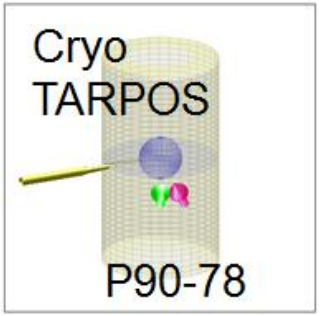


Image plate around periphery of primary diagnostic (framing camera or streak camera) for time-integrated imaging and verification of diagnostic positioner alignment.

Due to the harsh neutron environment (~10^9 n/cm^2), most time-integrated X-ray imaging at NIF is currently recorded on image plate or film.

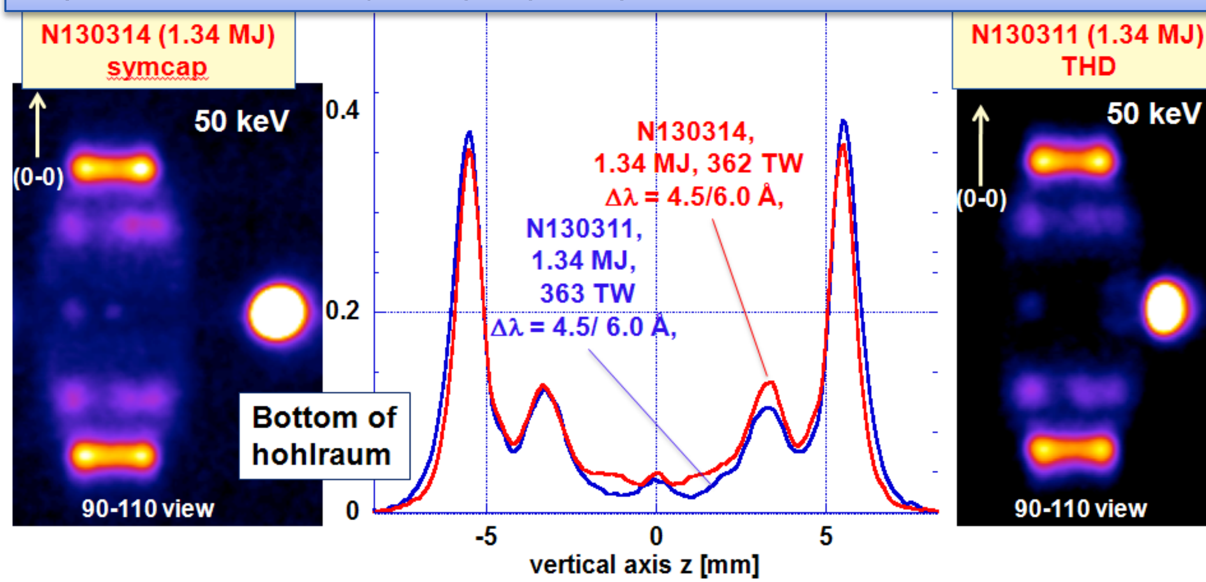




Time-integrated shape of ICF capsule implosion

P0	54.54	+/-	0.485	um
P2	3.375	+/-	0.126	um
P4	2.219	+/-	0.148	um
P2/P0	6.188	+/-	0.23	%
P4/P0	4.069	+/-	0.271	%

Equatorial Hard X-ray Imager (EHXI) -- View of emission from hohlraum



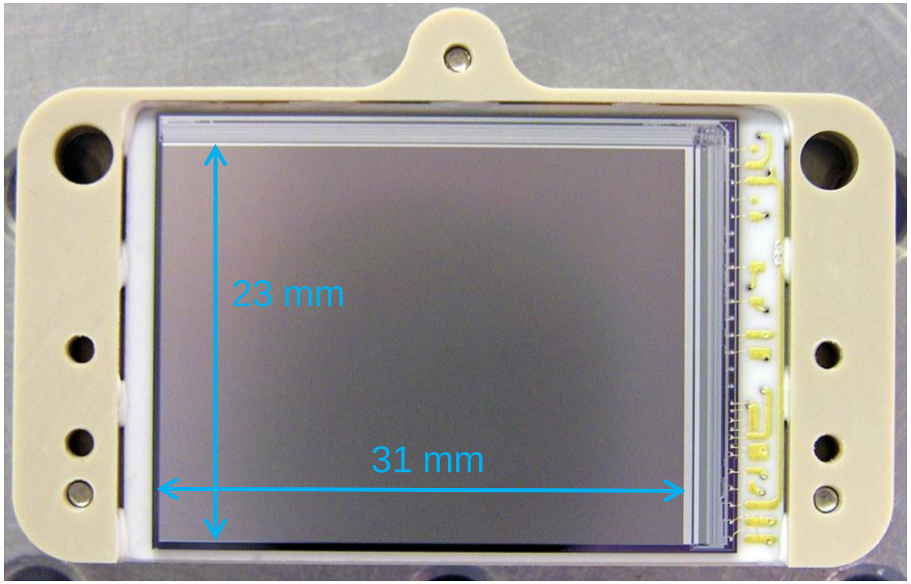
Advantages of Electronic Readout vs. Image Plate or Film

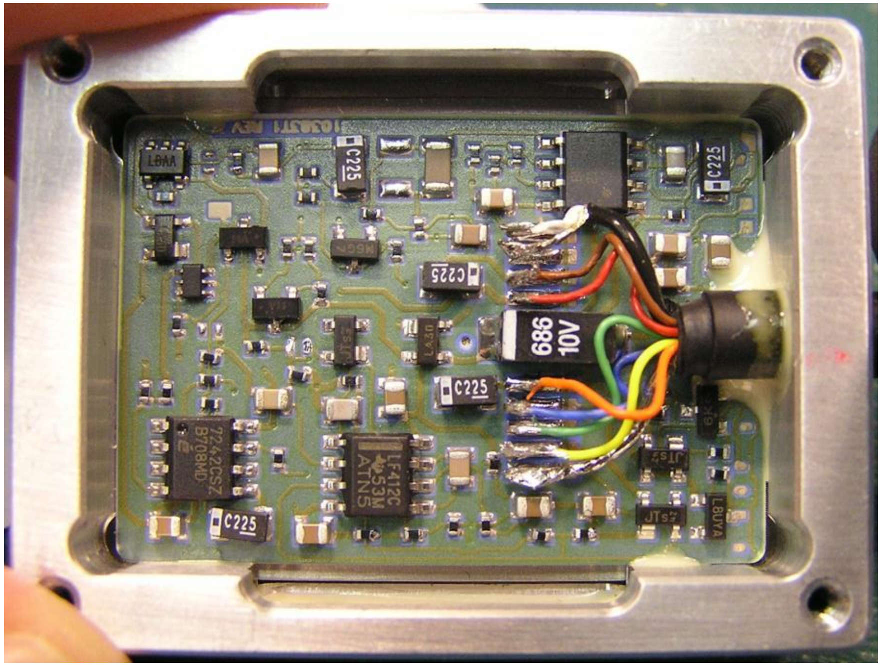
- **Rad hard Charge-Injection Device (CID) cameras can replace image plates in certain applications at NIF, leveraging significant advantages of electronic readout:**
  - ➢ **Data available within seconds after the shot instead of hours to days later for image plate or film**
  - ➢ **Much more efficient operation — No access to Target Chamber or diagnostics is required to retrieve the data**
  - ➢ **Enhanced safety — Technicians avoid rad dose they would otherwise receive going in to retrieve media**

- **One disadvantage of electronic sensors:**
  - **— Saturation limit of CIDs ~ 10x less than image plate; IP and film can obtain useable data on higher yield shots**

CID4150 Imager from Thermo Scientific, CIDTEC Cameras

- **Sensor selected based on successful use on ICF experiments at OMEGA (LLE)**
- **Highly compact device (31 x 23 x 5 mm) originally developed for dental X-ray imaging**
- **800 x 600 array, 38.5 µm (square) pixels; large full well capacity > 10^6 e^-**
- **Operated at room temperature (no thermo-electric cooling), in vacuum or in air**
  - **Integration time limited to < ~5 sec. due to high dark current and limitations of readout electronics. (Integration time used at NIF = 100 ms)**
- **Uncoated sensor => Direct X-ray detection**
  - **X-ray sensitivity range: 1 – 15 keV**
  - **Phosphor coatings are available to extend X-ray sensitivity up to ~ 100 keV. Phosphor thickness can be tailored to energy range of interest.**



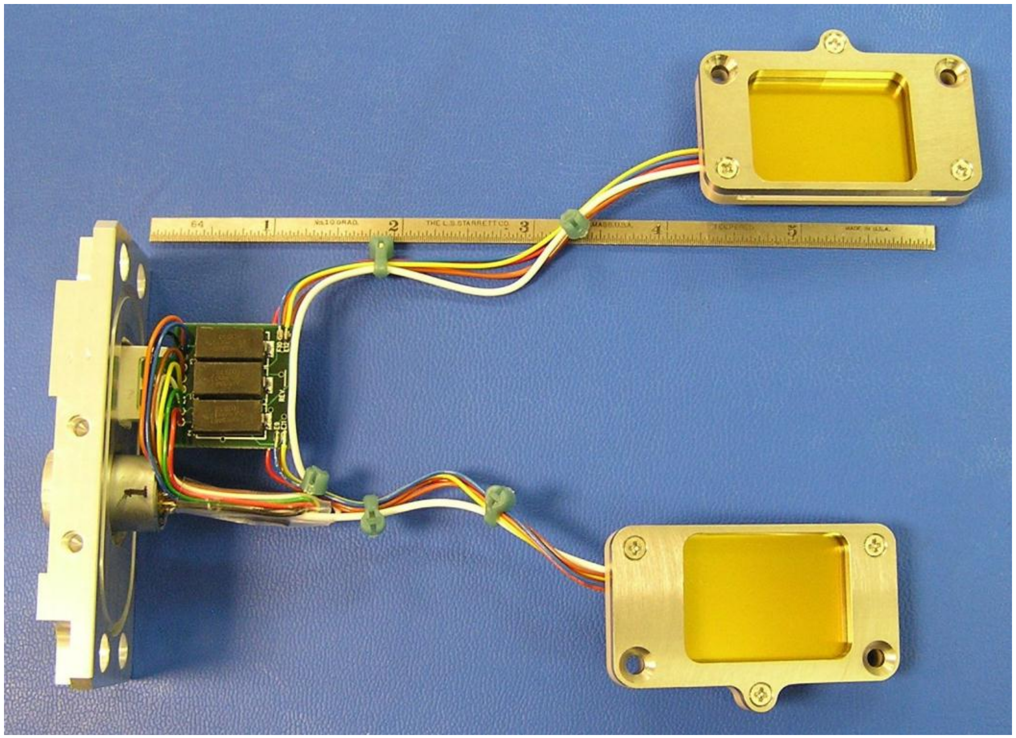


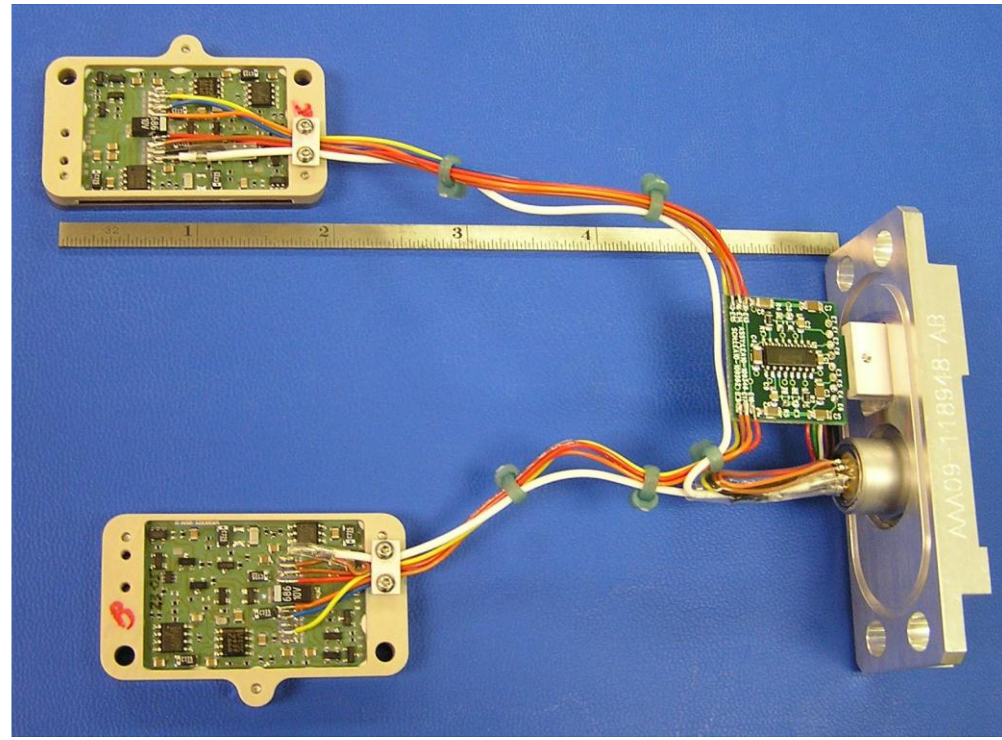
CID4150 Imager Characteristics (continued)

- **Rad Hard — Lifetime Dosage = 300 krad(Si) at 60 - 90 keV**
  - — This is ~ 20x higher than typical CCD cameras [10 - 20 krad(Si), n-channel]
  - — CIDs fab'ed using high-resistivity p-channel process. Other CID cameras available with lifetime dosage > 3 Mrad(Si) (^{60}Co source)
  - — Analog video output, 1.0 Vpp, using discrete analog components (more rad hard than high-density digital circuitry)
- **Readout is progressive @ 500 kHz => ~ 1 sec to read out 800 x 600 image**
  - — Nondestructive readout capability of CIDs not implemented for this camera
- **Analog output transmitted via coax. cable to 16-bit digitizer**
- **Dynamic Range (estimated by vendor) > 1000:1**
- **Limiting Resolution: 10 LP/mm**

CCXI Assembly for Fielding on DIM*-based Diagnostics at NIF

CCXI = CID Camera X-ray Imager





- 2 CID camera modules
- 3 mm thick tungsten frame shields edges of sensors, protects on-chip logic
- 25 µm Kapton® film, protective cover over face of sensor
- Small interface circuit board: DC power filters (EMI protection) and differential line receivers for CLOCK and TRIG signals

- Video signal (image) output via micro coax.
- All other signals via Tefzel-jacketed hook-up wire.
- All materials meet stringent NIF requirements for cleanliness and low outgassing

* DIM = Diagnostic Instrument Manipulator

CCXI Mounted on DIM-based Diagnostic

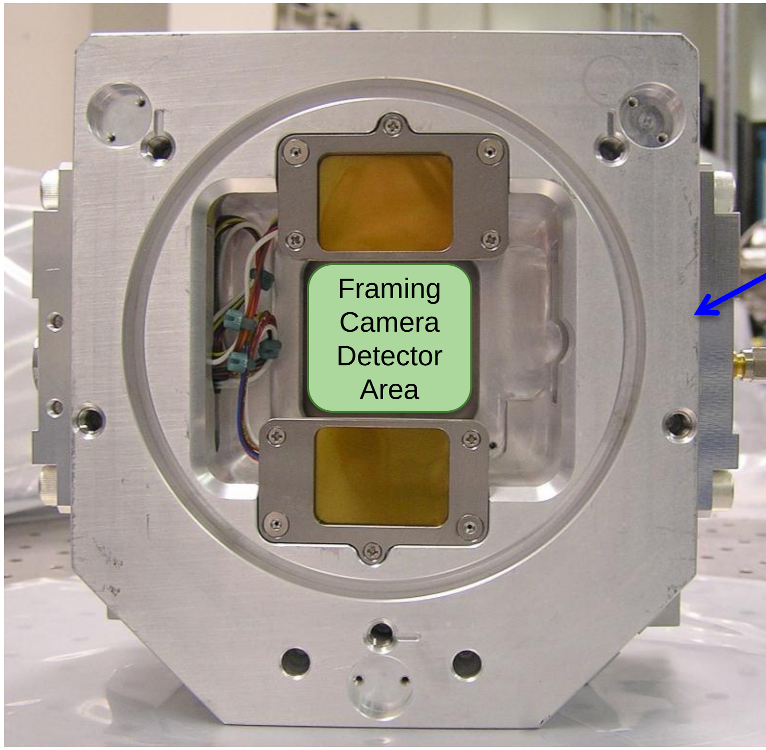
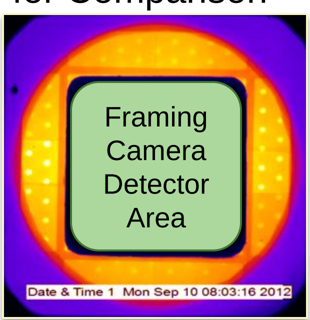
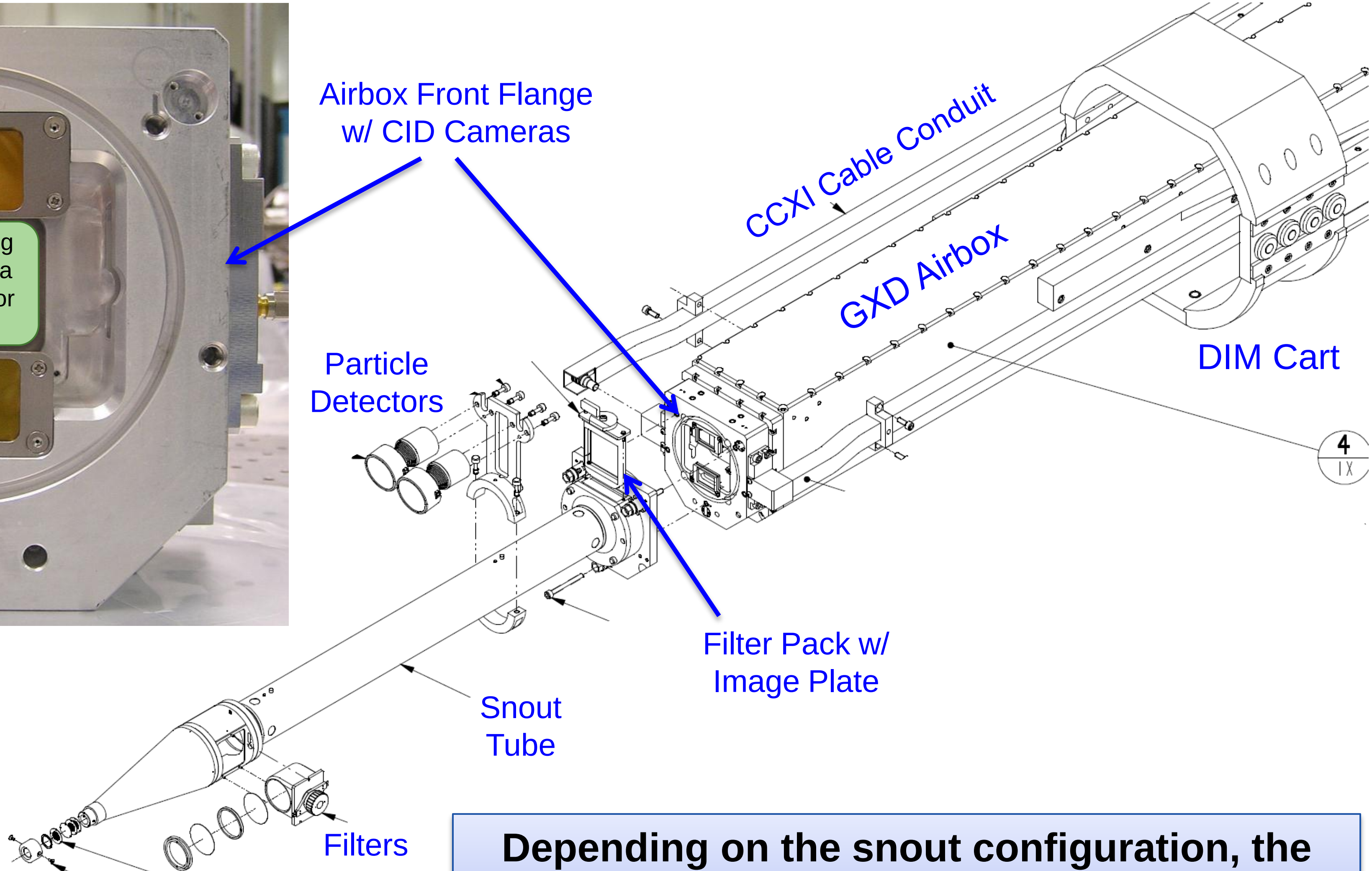


Image Plate Data
for Comparison

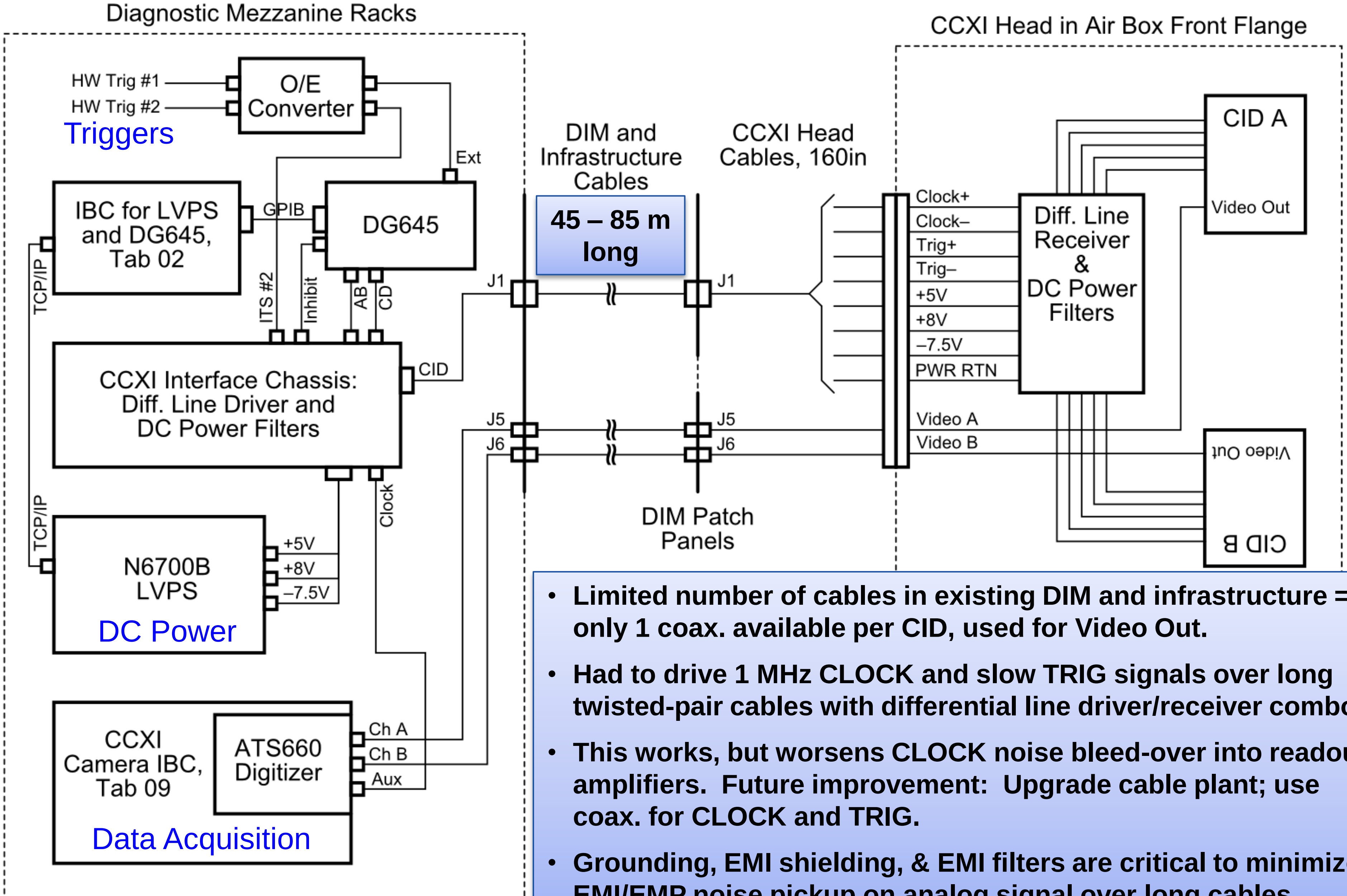




Depending on the snout configuration, the CID cameras sit ~ 125 cm from the target, where neutron fluence can exceed 10^9 n/cm^2

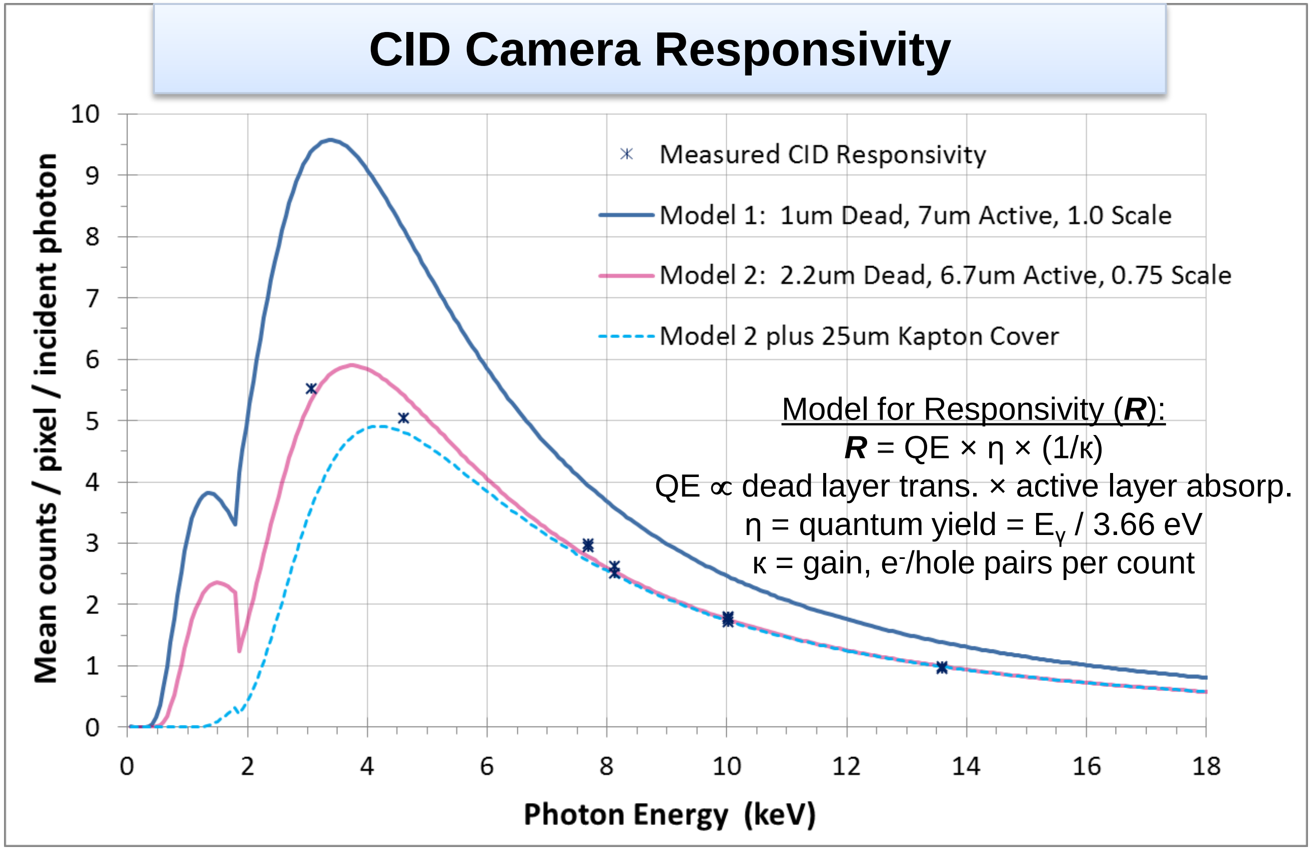
(Drawing excerpt from AAA10-106125-AA, GXD DLP Assy., 4x Mag.)

Electrical Design – CCXI System Schematic



- **Limited number of cables in existing DIM and infrastructure => only 1 coax. available per CID, used for Video Out.**
- **Had to drive 1 MHz CLOCK and slow TRIG signals over long twisted-pair cables with differential line driver/receiver combo.**
- **This works, but worsens CLOCK noise bleed-over into readout amplifiers. Future improvement: Upgrade cable plant; use coax. for CLOCK and TRIG.**
- **Grounding, EMI shielding, & EMI filters are critical to minimize EMI/EMP noise pickup on analog signal over long cables.**

CID Camera Calibration – Responsivity



Significant challenges to calibrate these CID cameras. Short exposure + limited X-ray flux from cal. sources + low responsivity of CIDs =>

- **Photon statistics in individual images overwhelmed by other sources of noise (readout and pattern noise)**
- **Large number of images (~50) required to improve signal-to-noise**
- **Background images must be acquired within seconds of X-ray images**

(See paper for additional details of how these challenges were overcome.)

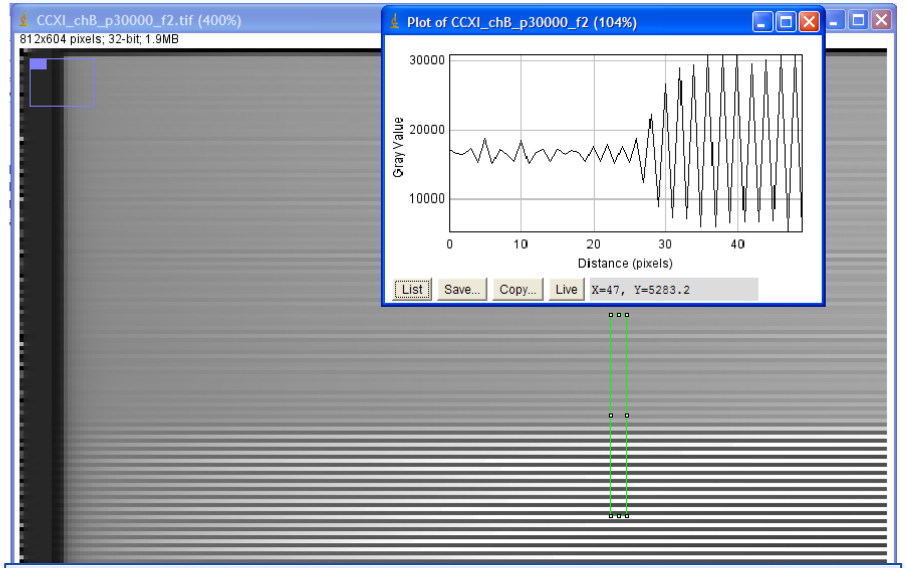
- **Responsivity measured at NSTec using Manson (3 - 7.7 keV) and HEX (8 - 14 keV) X-ray sources.***
- **Model 1 uses initial estimates — 1um dead layer, 7um active layer, κ = 56 e^-/hole pairs per count.**
- **Model 2 adjusted for better fit to data — 2.2um dead layer, 6.7um active. 0.75 scale factor accounts for errors in initial estimates of gain, pixel active area, and charge collection efficiency.**
- **25 µm Kapton® cover further reduces low energy response.**

*Haugh, M. J., et al., "Calibration of X-ray imaging devices for accurate intensity measurement," Powder Diffr. 27(2), 79-86 (2012)

CID Camera Calibration – Linearity and Resolution

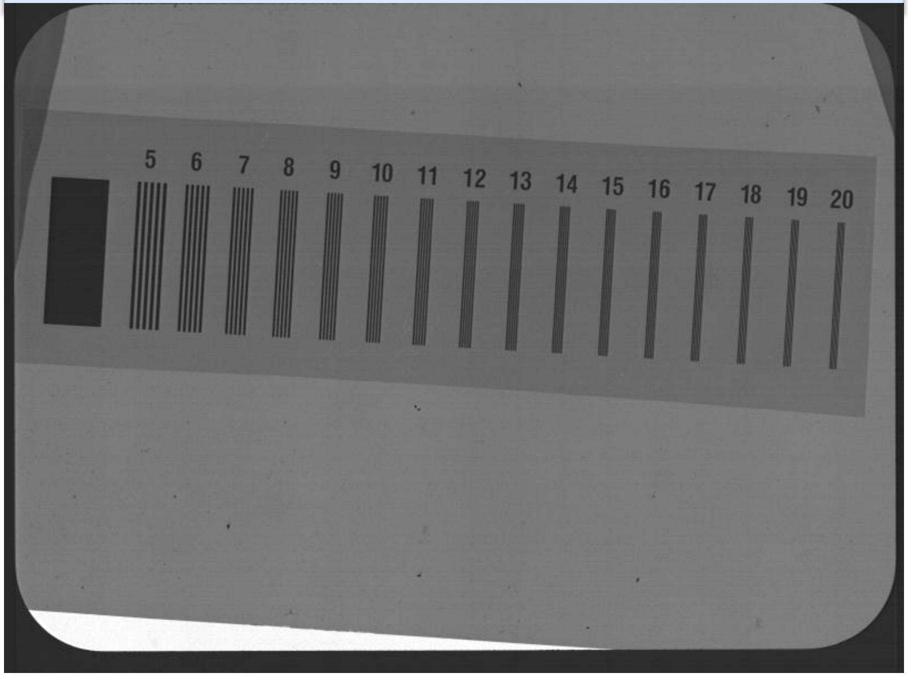
Linearity

- **Visible light used instead of X-rays to produce enough counts to span full linear range.**
- **Discovered nonphysical saturation behavior**
  - **For flat-field illumination: Output linear up to ~ 16,000 counts/pixel (~ 1 V), then output starts to “oscillate”, every other row high then low, producing bands (image below).**
  - **For small bright spot: Output linear up to ~ 20,000 counts/pixel (~ 1.2 V) if illumination confined to small region on sensor (such as pinhole image of ICF target).**
- **This appears to be a limitation of the integrated readout electronics (rated 1.0 Vpp), not the CID chip itself.**



CCXI image showing onset of saturation oscillation with alternating rows of high and low counts

Resolution



- **Illumination from Manson source, Ti anode, no filter (~ 4.6 keV X-rays)**
- **Average of 50 images, 1 sec. exposures, background-subtracted**
- **Dark outer edges are shadow of tungsten frame**

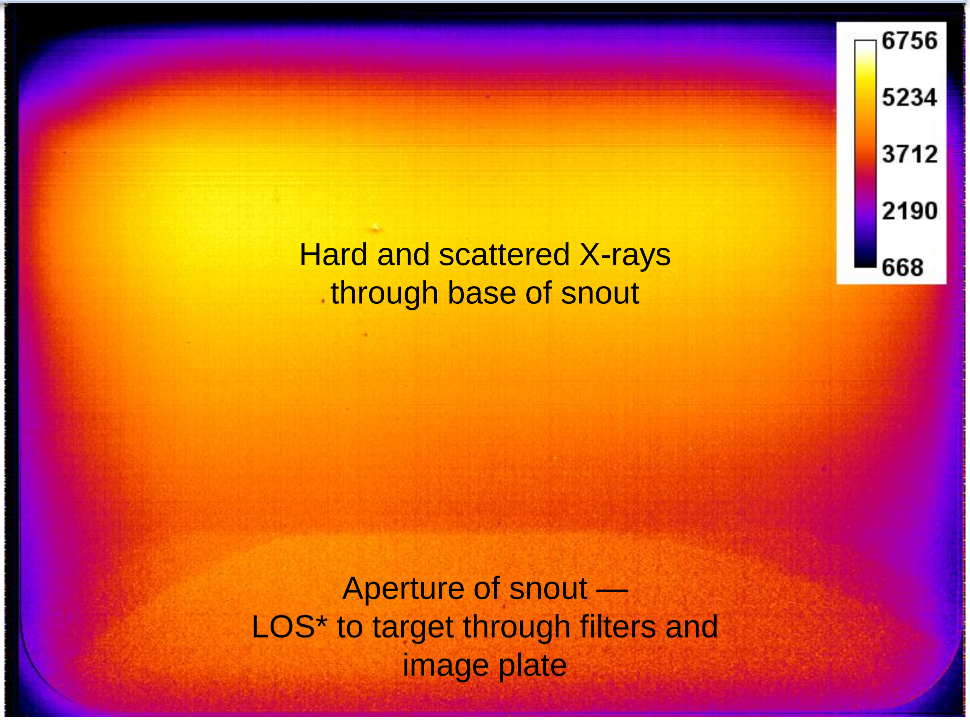
Limiting Resolution:

MTF* = 50% at ≈ 10 LP/mm

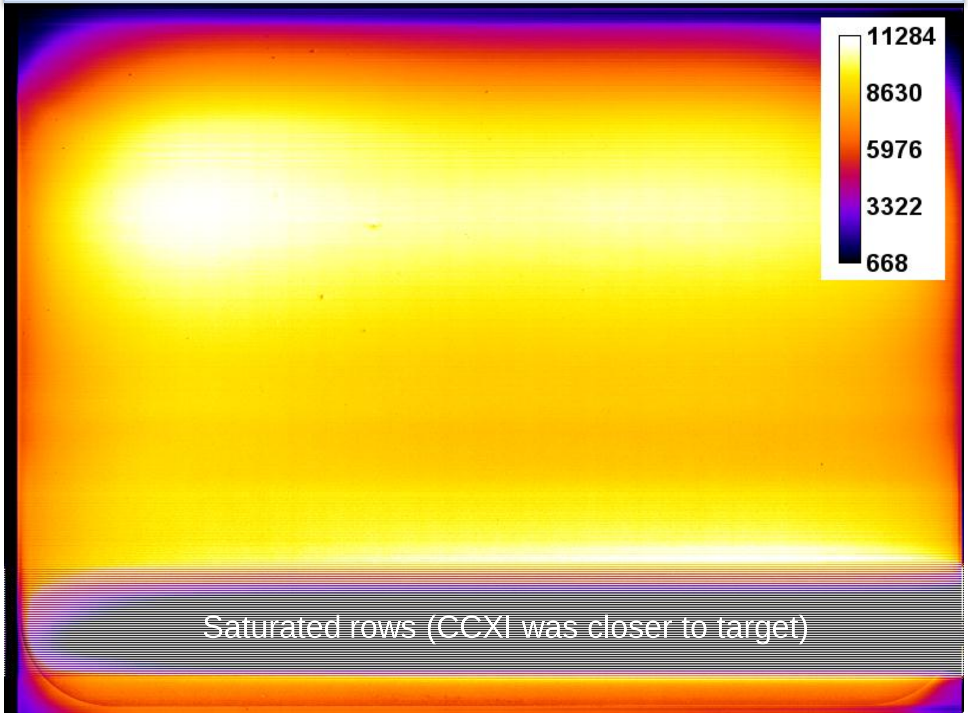
* MTF = Modulation Transfer Function

CCXI Images from Shots on NIF – Noise and Dynamic Range

N110807 (Symcap), 1.3 MJ, 417 TW, Yn (DD) = 3.7E+11
CCXI-2A at 125 cm, DIM 0-0, 12x Mag Snout



N110820 (Shock123), 822 kJ, 411 TW, Yn = Negligible
CCXI-2A at 71 cm, DIM 0-0, 1x Soft X-ray Snout



- **For these preliminary tests, no imaging line of sight for CCXI, just diffuse illumination through snout and filters**
- **Typical Noise (Std. Dev.) ≈ 200 – 400 cts (100 x 100 pixel center region of preshot background image)**
- **Saturation limit for broad illumination ≈ 16,000 cts => Dynamic range ≈ 40:1 – 80:1**

- **Saturation limit for small bright spot ≈ 20,000 cts => Dynamic range ≈ 50:1 – 100:1**
- **Noise could be reduced with cable upgrade and EMI shielding improvements.**
- **High dark current also eats away dynamic range by raising bias level of noise floor. Cooling the sensor would help, but would also add complexity.**

* LOS = Line of sight

CCXI Saturation Limits With High Neutron Fluence

- CCXI obtained usable data (see image to the right) w/ n-fluence 2.4E+7 n/cm² (Yn = 4.27E+12) and 4.3E+7 n/cm² (Yn = 8.5E+12)
- CCXI saturated on shots with n-fluence > 8.8E+8 n/cm² (Yn > 1.7E+14).
- Exact neutron saturation limit of CCXI not measured (no shots with Yn ~ 10^{13} range), but results above are consistent with results at OMEGA** and calculations* of CID saturation vs. image plate (table below).

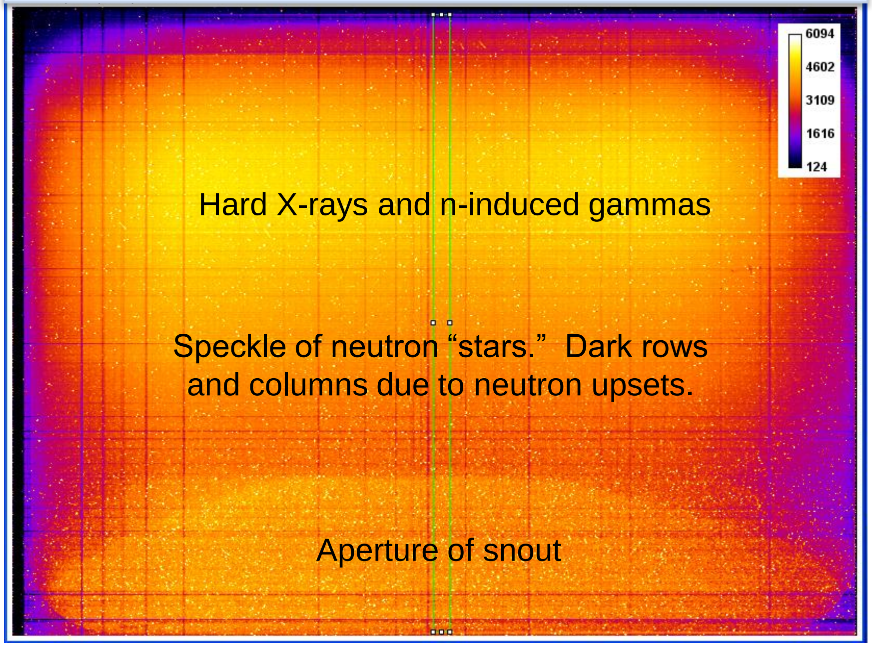
Estimated Saturation Limits* for CIDs vs. Image Plate

Detector:	BAS-SR Image Plate	CID4150 for CCXI
Pixel size	25um	38.5um
Material	BaFBr(Eu)	Si
Protection layer	PET ~7um	SiO2 ~1um
Sensitive layer	39 mg/cm2	1.63 mg/cm2
Energy absorption @ 10keV	97.5%	5.2%
Saturation limit	1.265E+5 PSL/mm2	1E+6 electron/pix
Signal saturation (absorbed)	**63 erg/cm2**	**0.40 erg/cm2**
14 MeV Neutron sensitivity	~1.3 keV/inc. n	130 eV/ inc. n
n-fluence equiv. to saturation	3E+10 n/cm2	1.9E+9 n/cm2
Practical n-fluence limit	3E+9 n/cm2	3E+8 n/cm2**
Practical Yn limit at 125 cm	**5.9E+14**	**5.9E+13**

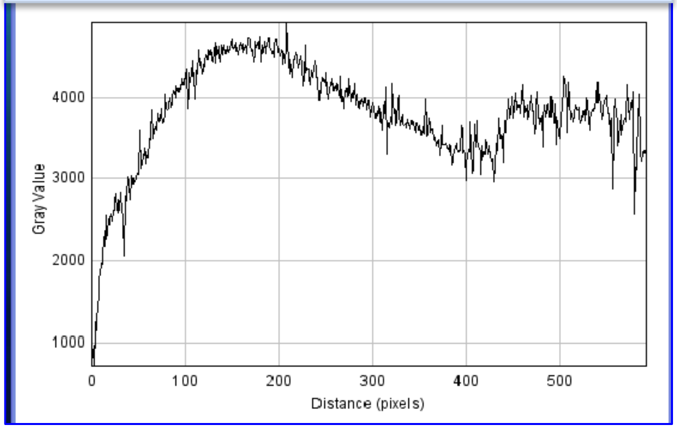
* Calculations by N. Izumi, LLNL, 8/15/2011

** Marshall, F. J., DeHaas, T., and Glebov, V. Y., Rev. Sci. Instrum. 81, 10E503 (2010)

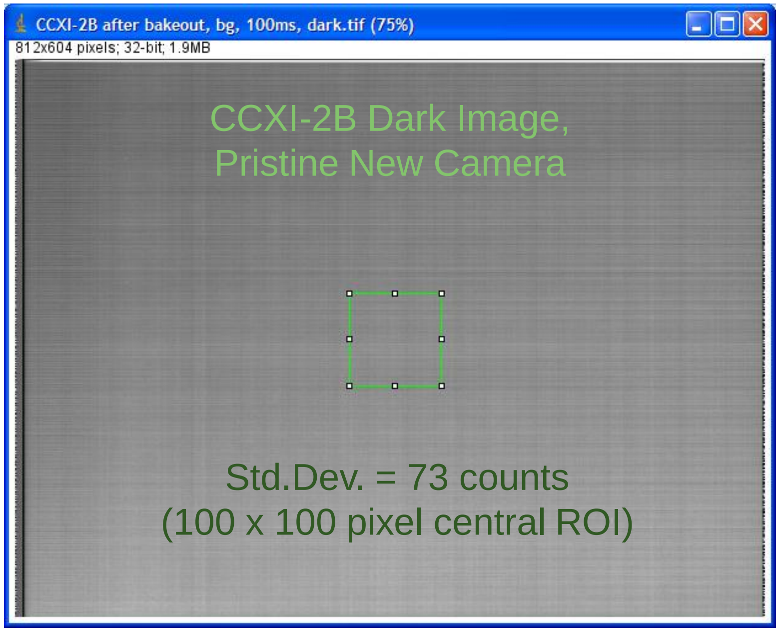
CCXI-2B Image from Shot N110804 (THD)
14 MeV n-Fluence = 2.4E+7 n/cm²



Vertical Line-Out

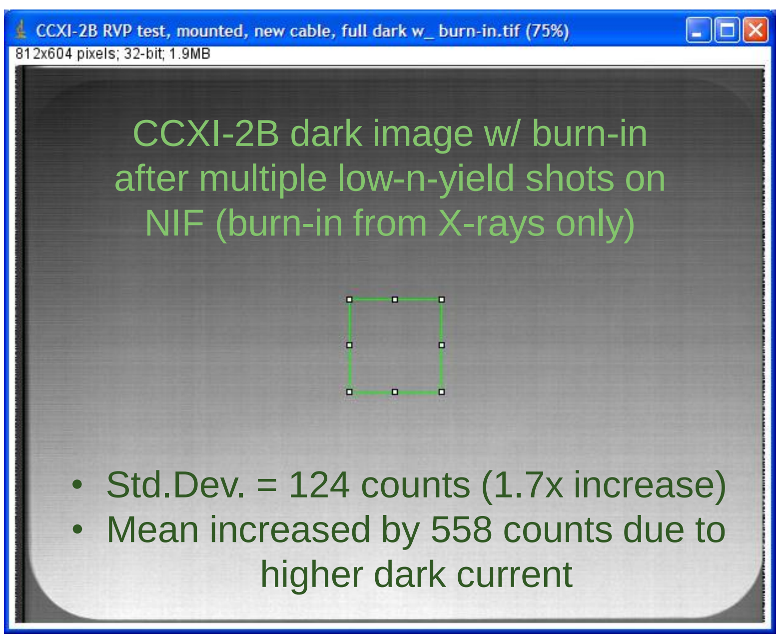


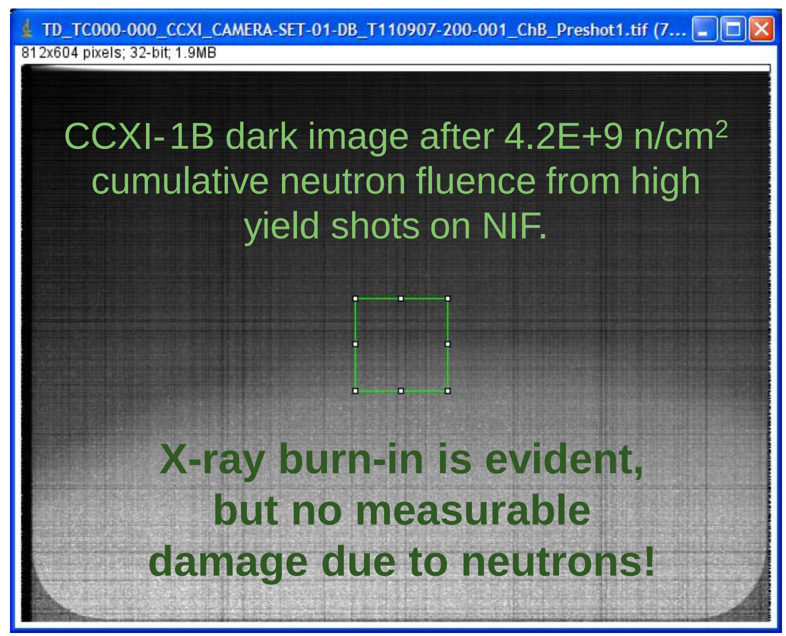
CCXI Survives High Fluence of X-rays and Neutrons with Minimal Damage



- After multiple low-neutron-yield shots at NIF, CCXI-2 had some X-ray burn-in damage as shown to the left. X-ray burn-in can be minimized with appropriate filtering.
- Series of high-neutron-yield shots (see table) with CCXI-1 at 125 cm from target (cumulative 14 MeV neutron fluence ~ 4.2 × 10^9 n/cm^2) — Images were highly saturated and cameras experienced upsets, but subsequent dry run images showed no measurable damage due to neutrons.

Shot ID	DT n Yield, 14 MeV	DT Neutron Fluence* at CCXI (n/cm^2)
N110608	1.93 × 10^{14}	9.8 × 10^8
N110826	1.72 × 10^{14}	8.8 × 10^8
N110904	4.50 × 10^{14}	2.3 × 10^9





* Includes primary DT neutron fluence only. Total fluence including scattered neutrons was higher than this.

Conclusions and Future Work

- **CID camera X-ray Imager has been successfully designed, built, calibrated, and fielded at NIF on DIM-based diagnostics (GXD and hGXI) in DIM 0-0 and in DIM 90-78.**
  - — **CCXI was not commissioned in DIM 90-315 due to shorts in infrastructure cable.**
- **CCXI calibration — Responsivity measured for X-rays from 3 – 14 keV. Linearity and Resolution also characterized. CIDs are suitable for various imaging applications at NIF.**
- **CCXI performance and radiation hardness have been evaluated at NIF in a harsh neutron environment.**
  - — **CCXI can acquire usable images up to ~ 10^8 n/cm^2 (shot yield of ~ 5×10^{13} with CID at 125 cm from target).**
  - — **CCXI images saturate at higher fluence, but CIDs survive with no measurable damage due to neutrons. (Tested up to 4.2×10^9 n/cm^2 cumulative DT neutron fluence.)**
- **Future Improvements and Applications:**
  - — **Upgrade cable plant to transmit CLOCK and TRIG signals via coax. instead of differential line pair, thereby reducing noise coupling into readout. Improve EMI shielding.**
  - — **Fine-tune delay of CLOCK signal to get optimal analog-to-digital samples where noise in readout signal is lowest.**
  - — **Adapt CID cameras for other imaging applications at NIF such as EHXI (Equatorial Hard X-ray Imager).**


NIF